Advanced Sensors for Real-time control of Advanced Natural Gas Reciprocating Engine Combustion

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Project Description and Objectives

Objectives:

To develop advanced sensors and control system for real-time combustion monitoring of advanced natural-gas reciprocating engines.

Proposed sensors include:

- NOx emission sensor -- Corona/spark discharge ion-mobility spectrometer (IMS).
- Fuel gas composition sensor -- Acoustic techniques, measurements of speed-of-sound and acoustic relaxation spectroscopy.

Project Team/Partnerships

- Argonne National Laboratory
  - Sensor development
- Northwestern University
  - Theoretical modeling of the acoustic sensor
- Commercial Electronics (Broken Arrow, OK)
  - Control electronics and system

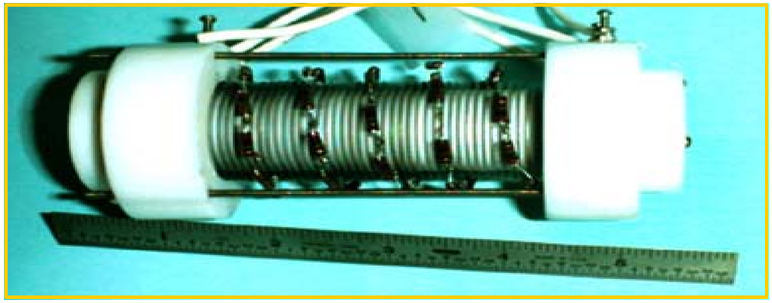
Task Definition and Activities

- Development of IMS NO_x sensor
  - Develop a corona/spark discharge ionization source
  - Design and test a laboratory prototype
- Development of fuel-gas composition sensor
  - Establish a theoretical model to predict acoustic relaxation spectra of natural gas
  - Design and test a laboratory acoustic fuel gas sensor
- Development of control system for engine combustion control
- Design and field tests of the control system and sensors

Milestones Completed and Planned

- Milestones completed
  - Development of non-radioactive IMS NO_x sensor.
    - Designed and tested a spark discharge negative ion source
    - Evaluated the sensor performance
    - Evaluated water-vapor effects and methods to reduce them
  - Development of acoustic fuel-gas composition sensor
    - Designed and tested a laboratory prototype
    - Evaluated the sensor performance
  - Final report
- Proposed future plan
  - Develop field prototype sensors
  - Conduct field tests

IMS Laboratory Prototype



Ion source

- Needle-surface (-140V) gap -- 0.25 cm
- Applied voltage -- -3.0/-4.0 KV

Shutter grid

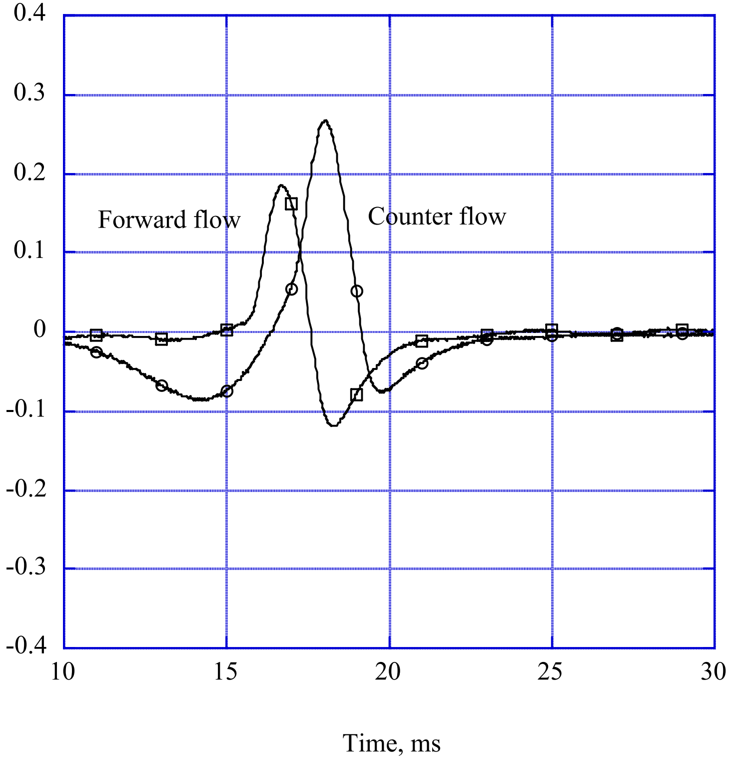
- Pulse width -- 2 ms
- Pulse voltage -- 140V
- Frequency -- 12.5 Hz

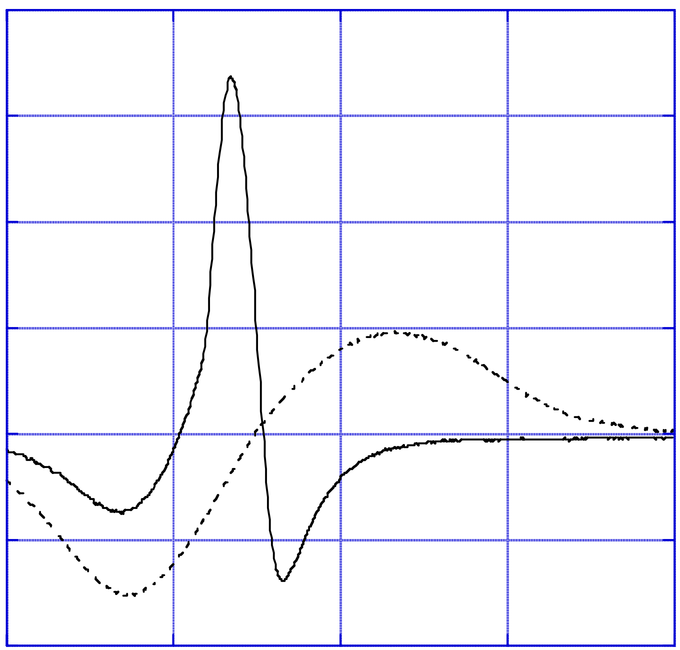
Drift tube electrical field -- 220 V/cm

Detection electronics

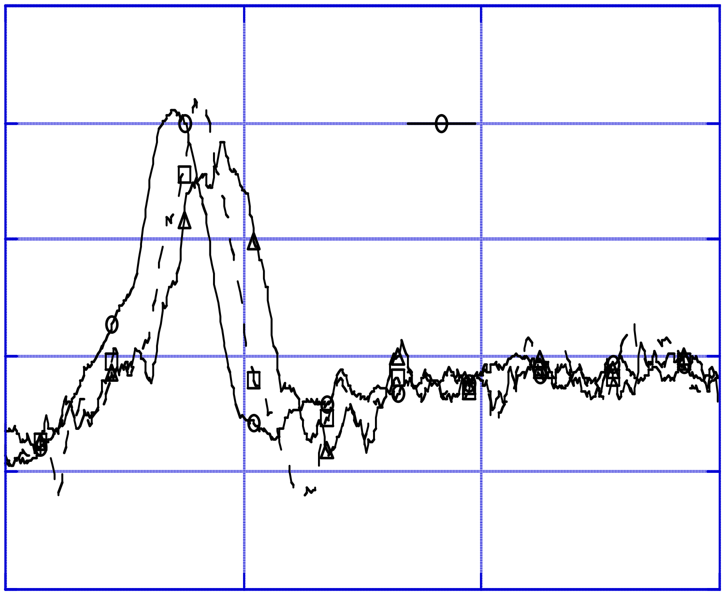
- 3 KHz LP filter
- Sensitivity -- 2 nA/V

Gas Flow Effect

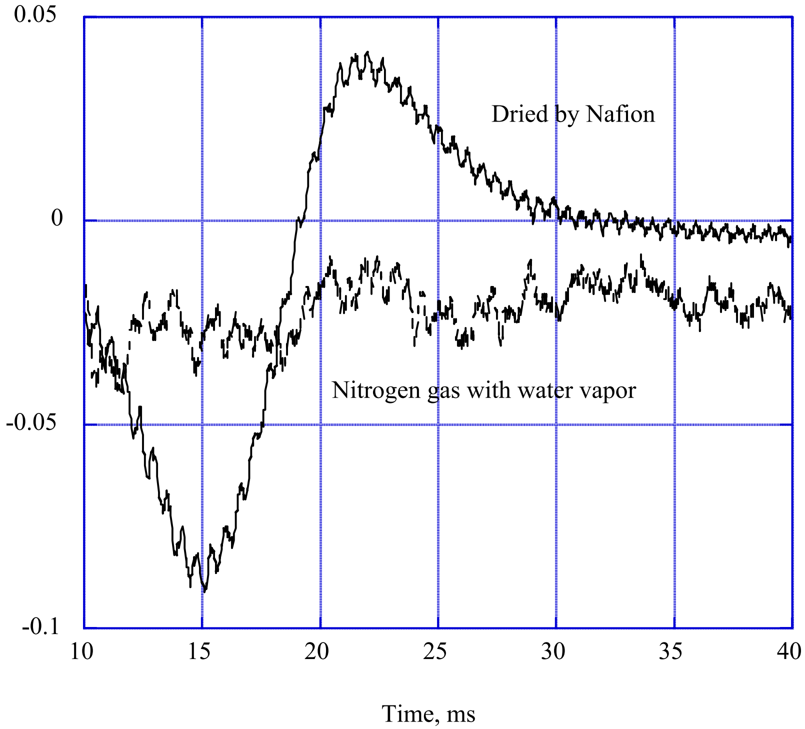




Moisture Effect and Methods to Reduce It

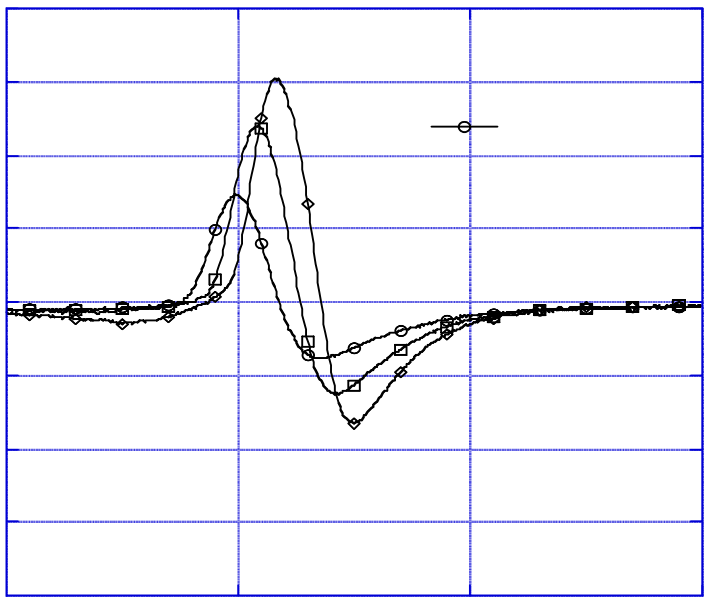


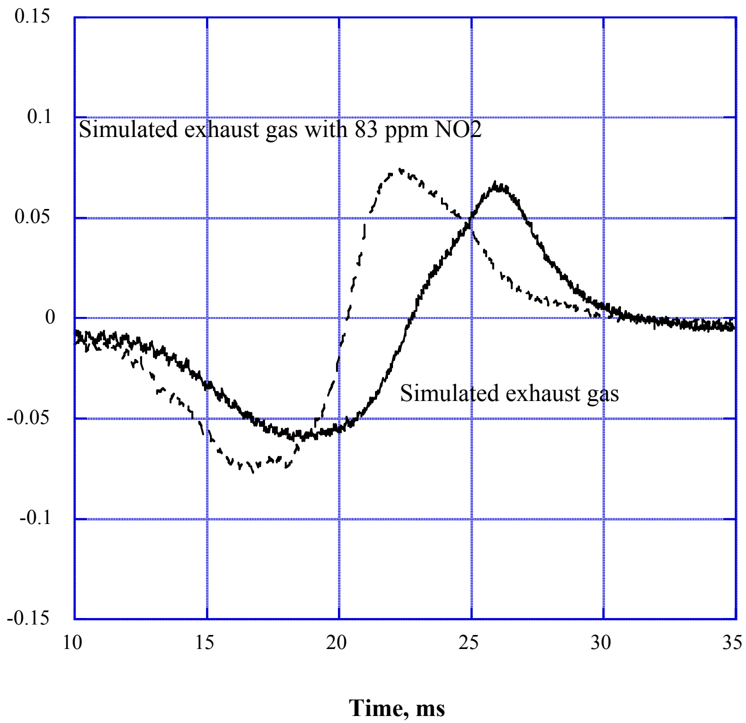
Thermoelectric cold plate



Nafion tubing

Carrier Gas Composition Effect





Nitrogen with air

Simulated exhaust gas

Peak Amplitude versus NOx Concentration

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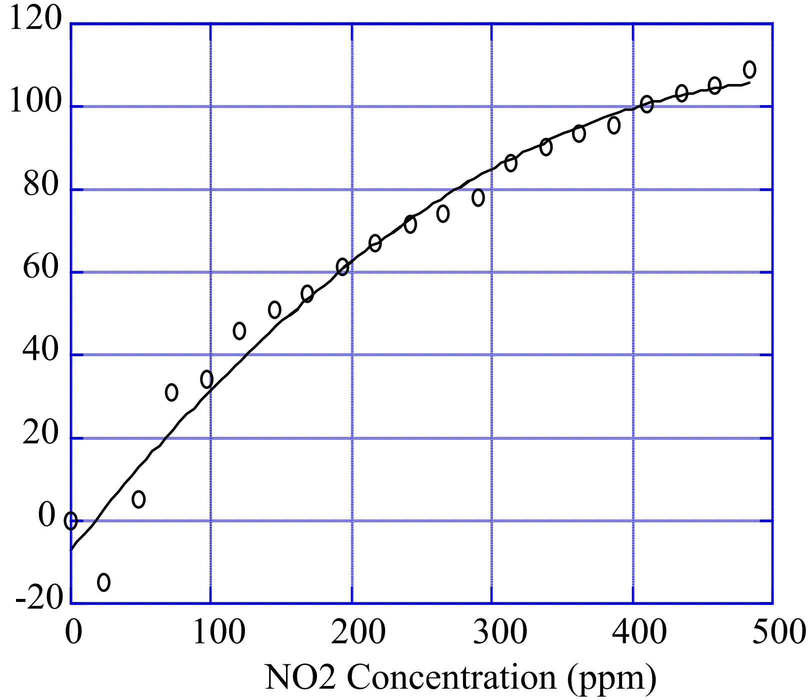

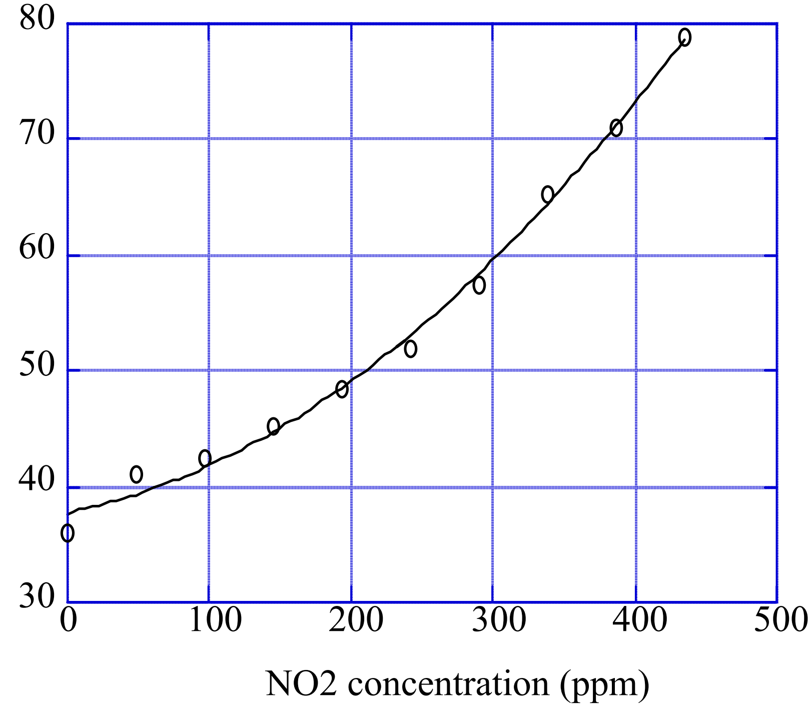

Dry nitrogen as carrier gas (2nA/V)

Simulated exhaust gas as carrier gas, (5nA/V)

IMS Performance as a NOx Sensor

- A nonradioactive spark-discharge ionization source was successfully developed and demonstrated.
- The sensor takes 80 ms to complete a sweep, and 100 sweeps are typically used to resolve a spectrum; thus the sensor response time is less than 10 s.
- Negative-ion current intensity has been correlated with NO_2 and NO_x concentrations up to 200 ppm with high sensitivity (5 ppm) and linear dependence.
- Change of spark-discharge current can be correlated with NO_2 concentrations up to 250 ppm.
- The effect of water vapor on the IMS spectrum was determined, and methods (e.g., use of Nafion tube) to reduce the effect are being examined.

Natural Gas Composition Sensor

System Setup

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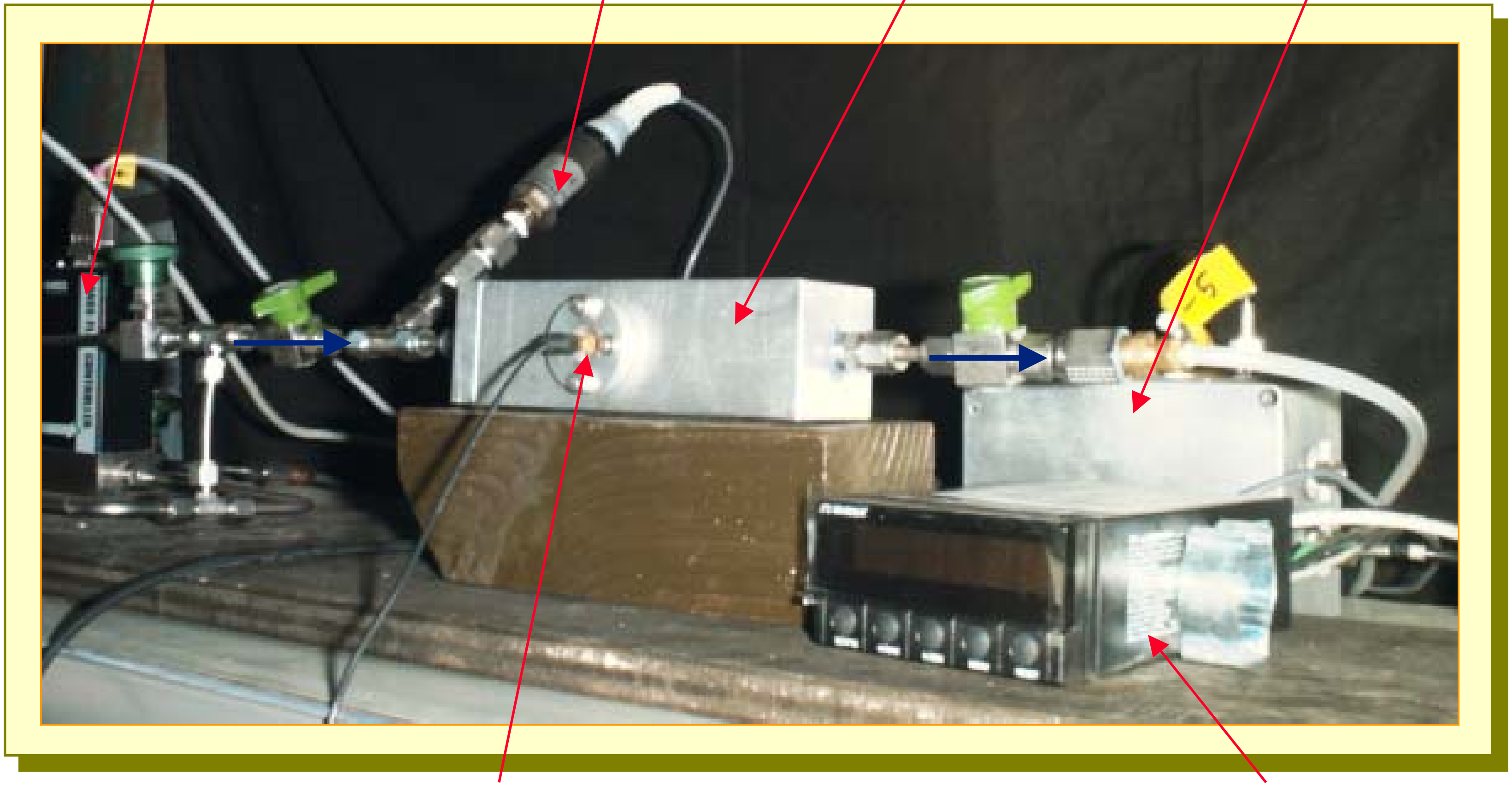
Mass Flow Controller

Pressure Sensor

Gas Mixing Chamber

Dual-Channel Pre-amp



Transducer

Pressure Sensor Monitor

Speed of Sound versus Fuel-gas Composition

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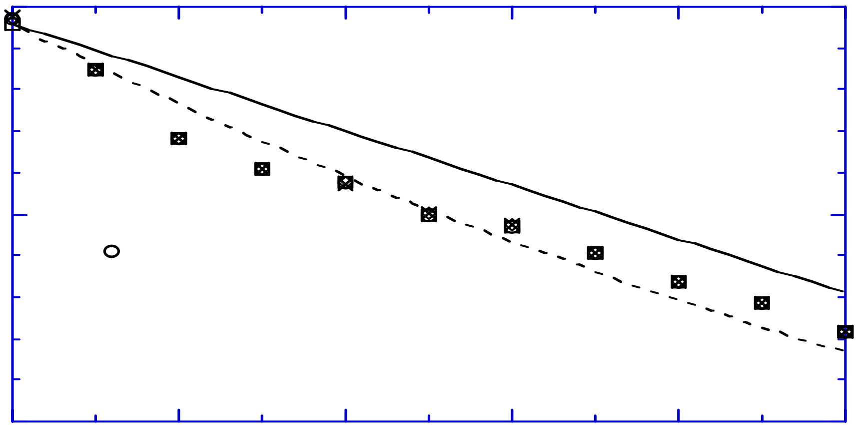
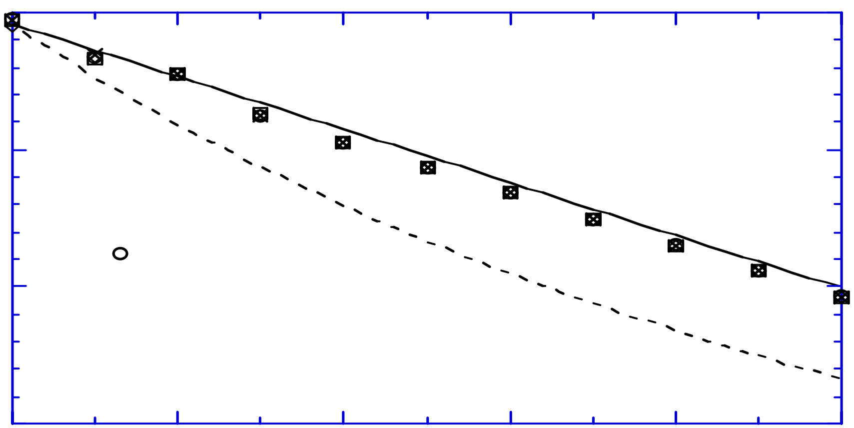


$$V(p,T)=\sqrt{\frac{\sum_{j=1}^{n}\phi_j\gamma_j RT}{\sum_{j=1}^{n}\phi_j M_j}\left(1-\sum_{j=1}^{n}\phi_j\beta_j p\right)}\quad \textbf{(Eq. 6)}$$

$$V=\sum_{j=1}^{n}\phi_j V_j \quad \textbf{(Eq. 7)}$$



Sound Attenuation versus Fuel-gas Composition

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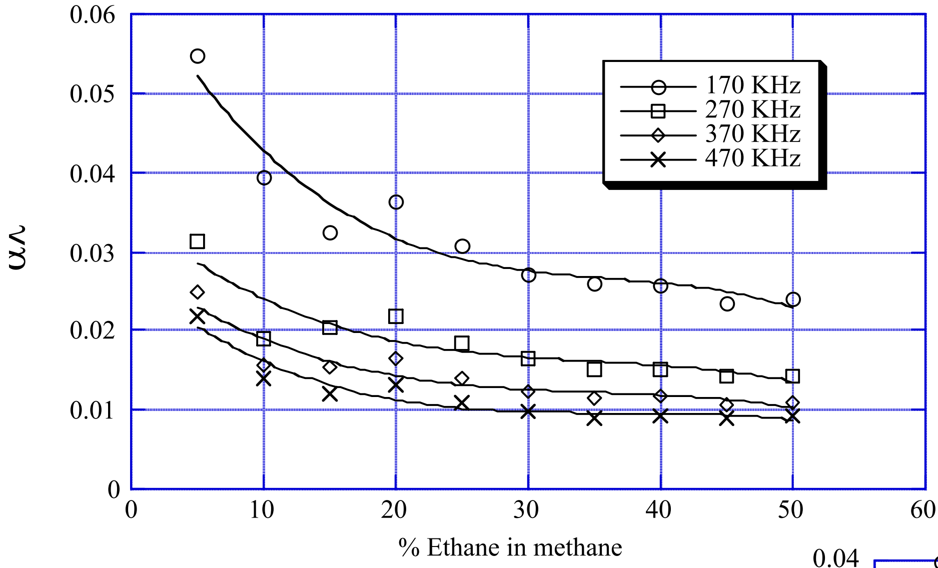

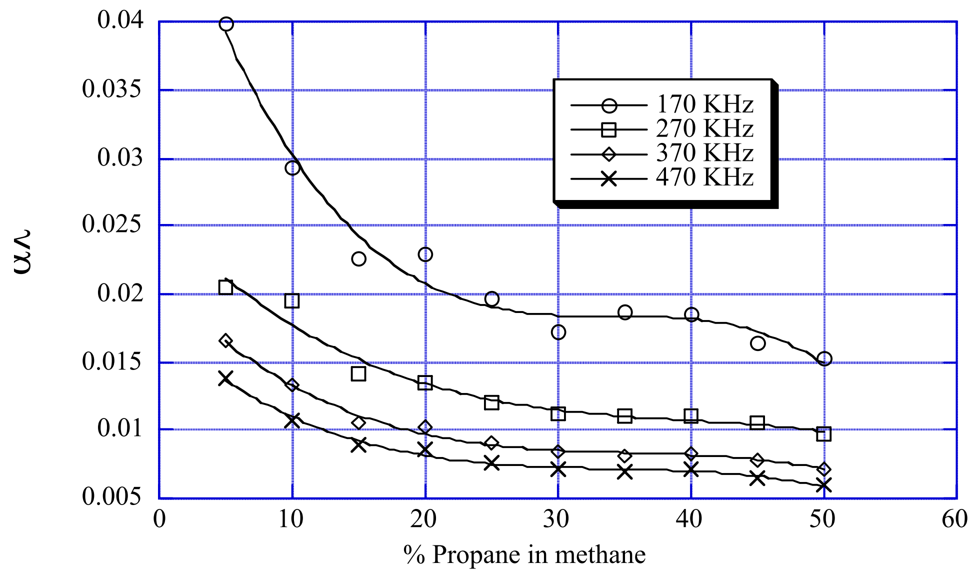

Acoustic Fuel-gas Sensor Performance

- Speed of sound can be used for binary gas mixture measurement with 0.1% sensitivity in composition change.
- Acoustic relaxation peak was detected for methane only in the frequency range of 0.1-0.5 MHz.
- Acoustic attenuation decreases as

  Methane > Ethane > Propane
- Fuel-gas composition of a methane/ethane/propane mixture may be determined by measuring both speed of sound and acoustic attenuation.

Key Technical Barriers and Strategies to Overcome Them

- IMS key technical barriers
  - Engineering issues of the field instrument
  - Spark discharge stability
- Strategies
  - Innovative approaches: Nafion gas conditioning, drift-tube design
  - Better needle electrode design, such as use of gold needle
- Acoustic sensor key technical barriers:
  - Temperature and pressure effects
  - Accuracy in quantifying other gases in methane
- Strategies
  - Establish a temperature and pressure calibration data base
  - Need additional measurements based on other sensor technologies

Impact on ARES

- ARES goals :To develop cleaner and more efficient next generation natural gas engines that will
  - Increase fuel combustion efficiency
  - Reduce emissions of NO_x, hydrocarbons, air toxics, and greenhouse gases
  - Reduce system costs and maintenance frequency
- Project impact on the goals:Reliable in-line sensors can provide continuous real-time monitoring of the combustion process and consequently improve the combustion efficiency.

Summary

- A low cost IMS NOx sensor can be built (potentially a very cheap one based on spark-discharge current alone, a patent disclosure filed)
- The acoustic sensor can be a good natural gas composition monitor (detects changes)
- Need support for development of field propotypes